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TIME: A FOOTPRINT OF IRREVERSIBILITY

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ABSTRACT. In the environment there exists a continuous interaction between electromagnetic radiation and matter. So, atoms continuously interact with the photons of the environmental electromagnetic fields. This electromagnetic interaction is a consequence of thermal non-equilibrium. It introduces an element of randomness into atomic and molecular motion, which leads to the decrease of the path probability required for the microscopic reversibility of evolution. Recently, an energy footprint has been theoretically proven in the atomic electron-photon interaction, as well as the well known spectroscopic phase shift effect and the results on the irreversibility of the electromagnetic interaction with atoms and molecules, experimentally obtained by R. O. Doyle in 1968. Here, we want to show that such a quantum footprint is nothing more than the generation of *time*.

In this short communication we want to show that time can be interpreted as the quantum footprint of irreversibility. To do so, we consider the interaction between a photon and an atomic-bond electron, *i.e.*, the transition from the fundamental state to an excited state, followed by the de-excitation to the previous fundamental state. This quantum process has been analysed by Lucia (2016, 2017, 2018); here, we use those results as a basis for the present developments and considerations.

At an atomic level photons can be absorbed by the atomic or molecular electrons, and an electronic energy transition occurs between the energy levels of two atomic stationary states. Then, the photons can also be emitted by the excited electrons when they jump down into the energy level of the original stationary state. During this phenomenon the electrons seem to follow a reversible energetic path, because they come back to the original stationary state of lower energy. But, as a consequence of the interaction between the electron and the photon, a footprint occurs in the atom or in the molecule. The results obtained by Lucia (2016, 2017, 2018) point out that the interaction between a photon and an electron in an atom affects the energy level of both the electron and the center of mass of the atom. So, it was analytically proved that the macroscopic irreversibility is a consequence of the microscopic irreversibility due to the photon-electron interaction or, from a macroscopic point of view, between the electromagnetic waves and matter.

The fundamental state function before the interaction can be obtained as solution of the Schrödinger equation (Feynman *et al.* 1964a; Landau and Lifshitz 1965):

$$\psi(\boldsymbol{r},\boldsymbol{R}) = \phi(\boldsymbol{r})\,\vartheta(\boldsymbol{R}) \tag{1}$$

where ϕ is the wave function of the electron, $\boldsymbol{r} = \boldsymbol{r}_N - \boldsymbol{r}_e$ are relative coordinates, $\boldsymbol{r}_N$ and $\boldsymbol{r}_e$ being the coordinates of the atomic nucleus and of the atomic electron, respectively; $\boldsymbol{R} = (m_N\boldsymbol{r}_N + m_e\boldsymbol{r}_e)(m_N + m_e)^{-1}$ are the coordinates of the center of mass before the photon-electron interaction, m_N and m_e being the mass of the nucleus and of the electron, respectively, and (Lucia 2016, 2017, 2018):

$$\begin{aligned} \vartheta(\boldsymbol{R}) &= \frac{1}{(2\pi)^{3/2}}\,\exp(i\boldsymbol{k}\cdot\boldsymbol{R}) \\ \boldsymbol{k} &= \sqrt{\frac{2M}{\hbar}E_{CM}}\,\boldsymbol{u}_{CM} \end{aligned} \tag{2}$$

where $E_{CM} = \boldsymbol{P}^2/2M$ is the kinetic energy of the center of mass, $\boldsymbol{P}$ being the momentum of the center of mass and M the total mass of the atom, $\boldsymbol{u}_{CM}$ is the versor of the momentum of the nucleus, and $\hbar = h/2\pi$, where h is Planck's constant.

Then, the photon incomes to the atomic electron which jumps from the fundamental state into an excited state and then jumps down to the fundamental state, with the emission of a new photon. The fundamental state function after this interaction can be obtained by quantum mechanics as (Feynman *et al.* 1964a; Landau and Lifshitz 1965; Lucia 2016, 2017, 2018):

$$\psi_f(\boldsymbol{r},\boldsymbol{R}) = \phi(\boldsymbol{r})\,\vartheta_f(\boldsymbol{R}) \tag{3}$$

where ϕ is the wave function of the electron and (Alonso and Finn 1968; Lucia 2016, 2017, 2018):

$$\begin{aligned} \vartheta_f(\boldsymbol{R}) &= \frac{1}{(2\pi)^{3/2}}\,\exp(i\boldsymbol{k}'\cdot\boldsymbol{R}) \\ \boldsymbol{k}' &= \sqrt{\frac{2M}{\hbar}\left(E_{CM} + \frac{m_e}{M}E_{ph}\right)}\,(\boldsymbol{u}_{CM} + \boldsymbol{u}_c) \end{aligned} \tag{4}$$

where E_{ph} is the energy of the incoming photon, $\boldsymbol{u}_c = \boldsymbol{c}/c$ is the versor of propagation of the electromagnetic wave, $\boldsymbol{c}$ being the velocity of light and c its value.

Recently, we have suggested a quantum thermodynamic approach to this photon-atomic electron interaction, proving that this atomic process leaves the footprint (Lucia 2016, 2017, 2018):

$$E_{ftp} = \Delta E_{ph} = \Delta E_{CM} = \left\langle \psi(\boldsymbol{r},\boldsymbol{R})\,|H|\,\psi_f(\boldsymbol{r},\boldsymbol{R})\right\rangle = \frac{m_e}{M}E_{ph} \tag{5}$$

where H is the Hamiltonian of the photon-electron interaction, *i.e.*, from a macroscopic point of view, the interaction between the electromagnetic wave and matter.

However, a quantity does not appear in this quantum approach of the transition between atomic steady states: time. But, something happens that forces us to introduce it. Indeed, the process that we have considered is completely irreversible, because the phase shift cannot be inverted, as it is well known in spectroscopy (Feynman *et al.* 1964a; Doyle 1968, 2014, 2016). Hence, we must introduce a quantity which shows this irreversibility. To do so, we consider that a photon is the quantum of the electromagnetic wave, and we can obtain its power by resorting to the power of the electromagnetic wave (Feynman *et al.* 1964b):

$$\dot{Q} = \left(\frac{1}{2} \varepsilon_0 c E_{el}^2 + \frac{1}{2\mu_0} c B_m^2 \right) A \tag{6}$$

where E_{el} is the electric field intensity, B_m is the magnetic field intensity, ε_0 and μ_0 are the electric permittivity and magnetic permeability in the vacuum, and A is the area of the interaction surface, *i.e.*, the area of the atomic surface, as usually considered in electromagnetism. From a thermodynamic point of view, in the interaction between the photon and the bond electron $\dot{Q}$ is just the incoming power into an open system (here, the atom). But, always from a thermodynamic point of view, E_{ftp} in Eq. (5) is nothing more than the energy wasted during the process (here, the excitation-de-excitation process of the atomic electron). Consequently, time can be introduced as the quantity which expresses the irreversibility of the interaction between the electromagnetic wave and matter, *i.e.*, the excitation and de-excitation of the atomic electrons in their interaction with the photons:

$$t = \frac{E_{ftp}}{\dot{Q}} = \frac{\dfrac{m_e}{M} E_{ph}}{\left(\dfrac{1}{2} \varepsilon_0 c E_{el}^2 + \dfrac{1}{2\mu_0} c B_m^2 \right) A} \tag{7}$$

In summary, we consider that our Universe is always in a non-equilibrium state; hence, continuous fluxes of energy occur in the form of electromagnetic waves (fluxes of photons, from a microscopic point of view). Consequently, the analysis of the interaction between such waves and matter is fundamental in the definition of both irreversibility and time itself. The atomic photon-electron interaction generates an energy footprint, in accordance with the experimental results obtained by Doyle (1968). In the analysis of this quantum process, time never appears. But, it can be defined by introducing the relation between the energy footprint and the power that is generated in the process, *i.e.*, the power of the electromagnetic wave. In such a way, time emerges up as the footprint of irreversibility.

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